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Weed control in a pigeon pea–wheat cropping system

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Abstract

Pigeon pea (*Cajanus cajan* (L.) Millsp.) seedlings compete poorly against the rapid growth of warm-season annual weeds. Weed control is required before this heat and drought-tolerant legume can be reliably grown in the U.S. southern Great Plains as a potential source of livestock hay between annual plantings of winter wheat (*Triticum aestivum* L.). Currently, no herbicides are labeled for use on pigeon pea grown in the U.S. Three years of replicated field experiments were conducted to determine the effects of applications (1× and 2× rates) of herbicides (pre-emergence, sulfentrazone + chlorimuron and metribuzin; post-emergence, imazapic and sethoxydim) on weed suppression, pigeon pea dry matter, and carry-over effects on a winter wheat crop. The most abundant summer weeds were broadleaf, and all herbicide treatments, except sethoxydim (grass herbicide), reduced weed densities compared to untreated plots without adversely affecting pigeon pea stands. Imazapic treatments provided the most effective weed control. Overall average pigeon pea dry matter ranged from 75 to 256 g m^{-2} with sethoxydim and the untreated control ≤ metribuzin ≤ sulfentrazone + chlorimuron ≤ hand weeded control ≤ imazapic. Compared to the hand-weeded control, imazapic treatments greatly reduced wheat dry matter (1×, 65% and 2×, 91%) and grain yield (1×, 59% and 2×, 93%). Imazapic should not be used unless nontransgenic imidazolinone herbicide tolerant wheat cultivars are planted. While the other herbicides decreased negative effects of weeds on pigeon pea dry matter without greatly affecting productivity of a following wheat crop, appropriate labels for each of these herbicides will be required prior to their use by southern Great Plains pigeon pea producers.

Keywords: Herbicide; Pre-emergence; Post-emergence; Biomass; *Cajanus cajan*; *Triticum aestivum*

1. Introduction

Pigeon pea (*Cajanus cajan* (L.) Millsp.), grown as a summer annual between plantings of winter wheat (*Triticum aestivum* L.), has been promoted recently as a potential source of grain and animal feed for southern Great Plains farmers and cattlemen seeking to diversify their agricultural options (Phillips and Rao, 2001; Rao et al., 2002a, 2003). In South Asia, double cropping of extra-short-duration pigeon peas and winter wheat has greatly increased, and many opportunities to improve this cropping system have been identified (Laxman Singh et al., 1996; Dahiya et al., 2002). Extra-short- and short-duration pigeon pea varieties tend to be tolerant to high temperatures and summer moisture deficits encountered in the southern Great Plains (Rao et al., 2002a, 2003). However, the relatively slow growth of the seedlings and juvenile plants compared to soybean and cowpea legumes (Brakke and Gardner, 1987) puts pigeon pea at a competitive disadvantage against the rapid growth of warm-season annual weeds (Callaway, 1992; Hepperly and Rodríguez, 1986) such as pigweed (*Amaranthus* spp.) and johnsongrass (*Sorghum halepense* (L.) Pers.). The need to overcome slow seedling growth and thereby reduce effects of weed interference has been targeted in the development of new extra-short-duration pigeon pea cultivars (Singh, 1996).

Attempts to expand research and demonstration plantings of pigeon pea from small plots to the large field scale, where weed control by hand is no longer an option, resulted in crop failures as a result of competition for resources by pigweed

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and johnsongrass (Rao, personal communication). The need for adequate weed control in pigeon pea plantings intended for use as a forage has been noted by others (Norman et al., 1980). Extensive research has been conducted on chemical weed control in pigeon pea grown primarily in India and Puerto Rico with Köppen climate regions (Aw, Cwa, and Bsh) different than those dominating the southern Great Plains (Cfa, Csb, and Bwk). In India and Puerto Rico, promising results were obtained with a number of pre-emergence herbicides as well as two types of post-emergence herbicides applied either as over-the-top selective or weed-directed non-selective treatments (Almodovar-Vega and Velez-Baez, 1980; Shetty, 1981; Semidey and Almodovar, 1987; Ali, 1991; Vaddi et al., 1999). However, some of these herbicides can reduce the growth of juvenile pigeon pea and at high application rates decrease nodule number, mass, and activity (Pahwa et al., 1988).

Before pigeon pea can be reliably grown in the southern Great Plains in a rotation with winter wheat, the suitability and benefits of chemical weed control must be evaluated. The objectives of our research were to evaluate the effects of pre- and post-emergence herbicides on weed suppression and dry matter productivity of pigeon pea and a subsequent winter wheat crop. Because no herbicides are registered currently for pigeon peas grown in the U.S., popular herbicides labeled for use on other legumes grown in the U.S. were selected and compared to hand-weeded and untreated (weedy-check) controls. Herbicides were selected on the basis of consultations with weed scientists (Oliver and Talbert, personal communication, 1997), their effectiveness for control of pigweed and warm-season grasses, and the available documentation on their use with crop rotations.

2. Materials and methods

Field experiments were conducted near El Reno, OK at the USDA-ARS Grazinglands Research Laboratory (GRL; 35°40′N, 98°00′W, elevation 414 m) on a Brewer silty clay loam soil (fine, mixed, superactive thermic Pachic Argiustolls). Two pre-emergence and two post-emergence herbicides were applied at two rates (Table 1) along with hand-weeded and untreated controls and evaluated in 1998–2000. The 10 treatments were arranged in a randomized complete block design with three replications. Each year each herbicide was applied in 1.02 L of solution to the same plot (each plot 4.87 m wide by 9.14 m long) using a Model BBM[1] CO_2 pressurized hand-held sprayer equipped with 8002VS TeeJet nozzle sprayer tips (R&D Sprayers, Opelousas, LA). Pre-emergence herbicides were applied within the first week after planting pigeon pea (*C. cajan* L. Millsp.; Georgia-2 line) inoculated with a multistrain inoculum commonly used for

Table 1
Herbicide, time, and rate of application in 1998–2000

Herbicide[a]	Application timing	Rate (a.i. g ha^{-1})	
		1×	2×
Sulfentrazone + chlorimuron	Pre-emergence	284	568
Metribuzin	Pre-emergence	370	740
Imazapic	Post-emergence	123	246
Sethoxydim	Post-emergence	148	296

[a] Sulfentrazone, *N*-[2,4-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl- 5-oxo-1*H*-1,2,4-triazol-1-yl]phenyl]methanesulfonamide; Chlorimuron, ethyl 2-[[[[(4-chloro-6-methoxypyrimiddin-2-yl)amino]carbonyl]amino]; Authority™, FMC Corp., Philadelphia, PA); Metribuzin, 4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4H)-one; Sencor® DF, Bayer Corp., Kansas City, MO; Imazapic, 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-methyl-3-pyridine carboxylic acid; Cadre®, BASF Corp., Research Triangle Park, NC; Sethoxydim, 2-[1-(ethyoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2cyclohexene-1-one; Poast Plus®, BASF Corp., Research Triangle Park, NC.

cowpea (*Vigna unguiculata* L.), but before its emergence about 10 days after planting. Post-emergence herbicides were applied 3–4 weeks after planting. The hand-weeded control plots were periodically hand weeded beginning 3–4 weeks after planting. The Georgia-2 line is an early maturing line that is photoperiod insensitive, short-stature, determinate in growth habit, and with similar total dry matter and seed yield as the extra-short-duration pigeon pea line ICPL 85010 when grown in the southern Great Plains following winter wheat (Rao et al., 2003).

Pigeon pea seed was planted at ≈2 cm depth in 20 cm rows at a rate sufficient to achieve a seedling density of at least 100,000 plants ha^{-1}. After the final sampling and harvest of the pigeon pea plots on 14 October 1998 (111 days after planting, DAP), the field remained fallow until planting pigeon pea the next year. After sampling and harvesting of the pigeon pea plots on 22 September 1999 (120 DAP) and 13 October 2000 (98 DAP), the field was prepared and planted with ‘TAM 101’ winter wheat (*T. aestivum* L.) in 20 cm rows at a seeding rate of about 112 kg seed ha^{-1}. Winter wheat plots were not fertilized with N to prevent effects of residual fertilizer N on our estimates of pigeon pea N_2 fixation (37.6 ± 2.1% of plant N derived from atmosphere; overall $\bar{x} \pm$ S.E. for 1998 and 1999) based on ^{15}N natural abundance differences as measured by isotope ratio mass spectrometry.

Rainfall and daily average temperature data were obtained from the El Reno, Oklahoma Mesonet site located within 3 km of the experimental plots at the USDA-ARS GRL. Data reported begins January 1998 (5 months before planting the first pigeon pea crop) and ends June 2001 with the harvest of the final winter wheat crop (Fig. 1).

2.1. Yearly pigeon pea cultural practices

Winter wheat stubble remaining after grain harvest in 1998 was burned June 18 before broadcasting and disking

[1] Mention of trade names and company names in this article is solely for the benefit of the reader and does not imply recommendation or endorsement by the authors or the U.S. Department of Agriculture.

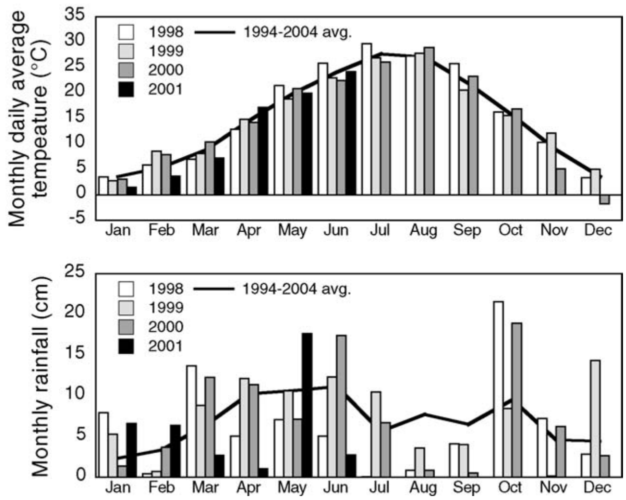

Fig. 1. Monthly daily average air temperature and monthly rainfall totals measured at the El Reno Oklahoma Mesonet site located within 3 km of the field research plots at the Grazinglands Research Laboratory. Data for 2001 not presented beyond June when the 2000–2001 wheat crop was harvested. Last data entry for 1994–2004 average was month of June.

60 kg ha^{-1} of P fertilizer into the soil on June 22. Pigeon pea was planted June 25. Plots were sprinkler irrigated on July 2 and 9, 1998 (4.5 cm each, total 9 cm). In April 1999, the winter fallow plots received a broadcast application of 60 kg P ha^{-1} and were disked to incorporate the fertilizer and control cool-season annual weeds. Pigeon pea was planted 25 May 1999. Winter wheat stubble remaining after sampling and harvesting the 1999–2000 wheat crop was burned on 13 June 2000. Again, 60 kg P ha^{-1} was broadcast and the soil disked to incorporate the fertilizer the day before planting pigeon pea on 7 July 2000. Plots received a single application of 2.5 cm of water by sprinkler irrigation 13 July 2000.

2.2. Plant density, dry matter, and N measurements

In each plot and at each periodic sampling date, two randomly selected 0.64 m^2 circular areas were marked by tossing a plastic hoop into the plot. The distance between the boundary of the plot and the closest edge of the hoop exceeded 0.5 m. Weed and pigeon pea densities within the hoop were estimated by counting the number of weeds exceeding a diameter of 2.5 cm and the number of pigeon pea plants. Aboveground dry matter measurements of weeds and pigeon pea were measured at the last sampling (late September or mid October) by hand clipping plants within the plastic hoop to a height of 2.5 cm, separating the weeds from the pigeon pea plants, and then drying the plants to a constant weight with a forced-air oven at 65 °C. Total aboveground dry matter of wheat plants at harvest maturity (first week of June) was determined by hand clipping plants within the plastic hoop to a height of 2.5 cm and then drying as described above. For the 2000–2001 wheat crop only, grain was separated from the total aboveground sample and used to estimate grain yield, tissue N concentrations, and total aboveground N accumulation. To measure total N, oven-dried tissue was ground with a cyclone mill to pass a 1 mm screen and then assayed by automated flash combustion using a LECO CHN-1000 analyzer (LECO Corp., St. Joseph, MI).

2.3. Statistical analyses

The same field site was used for all 3 years and each treatment was repeated on the same plot. Significance of treatment effects was evaluated by analysis of variance procedures (SAS Institute, 2002). Data were analyzed as a split-plot in time experiment with years and treatments as fixed effects. Winter wheat data for grain yield, grain N concentration, and total aboveground N accumulation of the 2000–2001 crop were analyzed as a randomized complete block design experiment.

3. Results

3.1. Pigeon pea and weed densities

3.1.1. Early season

Average pigeon pea plant densities among the weed control treatments before application of post-emergence herbicides were not significantly different (Table 2). Although not significantly different, the seedling stand densities of pigeon pea in 1998 and 1999 were numerically similar and 50% less than that of 2000. Except for the sulfentrazone + chlorimuron (2×) and metribuzin (2×) treatments, the pigeon pea seedling stands among the treatments in 2000 were substantially greater than those in 1999 and 1998 (Table 2).

The presence of broadleaf weeds was substantially different among years. Average broadleaf weed density in 1999 markedly exceeded those in 1998 and 2000 by 7–4-fold, respectively (Table 2). Within the untreated plots, the abundance of broadleaf weeds in 1999 was more than 7- to about 2-fold greater than in 1998 and 2000, respectively. Among the pre-emergence herbicide treatments, there was a trend for more effective control of broadleaf weeds at the higher herbicide rate, but only in 1999 was this trend significant when metribuzin was applied at the higher rate. The density of grass weeds was substantially less than the broadleaf weeds and in 1999, when broadleaf weeds were most abundant, no grasses were observed among any of the treatment plots including untreated plots (Table 2). Averaged across treatments, grass density in 2000 exceeded densities in 1998 and 1999 when measured within 4 weeks of planting.

3.1.2. Late season

Treatment × year and treatment main effects were not significant for pigeon pea stand densities within 4 weeks of

Table 2
Seedling densities (plants m^{-2}) before application of post-emergence herbicides

Treatment	Pigeon pea				Broadleaf weeds				Grasses			
	1998	1999	2000	Average	1998	1999	2000	Average	1998	1999	2000	Average
Hand-weeded	7.9	8.6	19.9	12.2	4.5	31.8	0.0	12.1	0.3	0.0	0.0	0.1
Untreated[a]	8.2	7.3	20.4	12.0	8.7	66.4	35.8	36.9	4.2	0.0	5.9	3.4
Sulfentrazone + chlorimuron (1×)	6.0	9.2	15.7	10.3	2.9	13.9	0.0	5.6	0.8	0.0	2.1	1.0
Sulfentrazone + chlorimuron (2×)	8.9	10.7	13.6	11.1	0.0	2.4	0.5	1.0	0.5	0.0	1.8	0.8
Metribuzin (1×)	6.6	8.7	18.6	11.3	6.3	35.9	1.0	14.4	0.8	0.0	3.7	1.5
Metribuzin (2×)	9.7	9.7	13.1	10.8	0.3	9.4	0.3	3.3	0.0	0.0	7.6	2.5
Average	7.9	9.1	16.9		3.8	26.6	6.3		1.1	0.0	3.5	

Source of variation	Pigeon pea ANOVA		Broadleaf weeds ANOVA		Grasses ANOVA	
	$P > F$	LSD $_{0.05}$	$P > F$	LSD $_{0.05}$	$P > F$	LSD $_{0.05}$
Treatment (T)	0.632	–	<0.001	11.2	0.102	–
Year (Y)	0.054	–	0.030	15.9	0.033	2.3
T × Y	0.002	3.41	0.016	18.8	0.207	–

Values are means of two separate counts about 1-week apart and between 2- and 4-weeks after planting.
[a] Plant counts for each replication were means of the untreated plot and four additional plots assigned to the post-emergence herbicide treatments not yet applied.

harvest. The yearly average late season pigeon pea stand in 2000 was nearly 3.5-fold greater than those in 1998 and 1999 (Table 3), which corresponds to the trend observed for the stands before the application of post-emergence herbicides (Table 2).

Among the herbicide treatments, the post-emergence imazapic treatment was equally effective for broadleaf weed control at either application rate and was not significantly different from the hand-weeded treatment (Table 3). In contrast, for the sulfentrazone + chlorimuron and metribuzin treatments, the higher application rate was more effective at reducing broadleaf weed density than the lower rate, and was less effective at controlling broadleaf weed population than the imazapic and the hand-weeded treatments. Sethoxydim (grass herbicide) had no effect on broadleaf weed density, which was not significantly different from that of untreated plots. Compared to broadleaf weeds, grasses were generally not abundant (see Table 2, early season grass weeds), and the already low late-season grass density was reduced further by nearly all of the herbicide treatments (Table 3).

3.2. Weed and pigeon pea aboveground dry matter

Total weed dry matter was reduced most effectively by the post-emergence herbicide imazapic. Averaged across all

Table 3
Plant densities (plants m^{-2}) within 4 weeks of harvest

Treatment	Pigeon pea				Broadleaf weeds				Grasses			
	1998	1999	2000	Average	1998	1999	2000	Average	1998	1999	2000	Average
Hand-weeded	6.6	6.5	20.7	11.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Untreated[a]	1.6	4.4	17.6	7.9	4.7	32.9	65.3	34.3	0.2	0.0	1.6	0.6
Sulfentrazone + chlorimuron (1×)	6.1	5.8	21.7	11.2	2.8	12.6	10.5	8.6	0.0	0.0	0.8	0.3
Sulfentrazone + chlorimuron (2×)	6.1	6.6	18.6	10.4	0.5	3.3	5.5	3.1	0.0	1.3	0.3	0.5
Metribuzin (1×)	4.5	5.5	19.6	9.9	2.6	19.1	4.5	8.7	0.0	0.3	0.5	0.3
Metribuzin (2×)	6.6	5.5	16.8	9.6	0.3	8.7	2.9	4.0	0.0	0.3	0.0	0.1
Imazapic (1×)	5.9	5.5	22.0	11.1	0.9	0.0	0.0	0.3	0.3	0.0	0.5	0.3
Imazapic (2×)	8.0	5.9	20.7	11.5	0.2	0.0	0.3	0.1	0.5	0.4	0.0	0.3
Sethoxydim (1×)	5.1	4.9	19.1	9.7	4.0	33.8	56.0	31.3	0.5	0.0	0.0	0.2
Sethoxydim (2×)	5.1	4.4	16.5	8.7	4.7	29.9	58.3	30.9	0.0	0.0	0.3	0.1
Average	5.6	5.5	19.3		2.1	14.0	20.3		0.2	0.2	0.4	

Source of variation	Pigeon pea ANOVA		Broadleaf weeds ANOVA		Grasses ANOVA	
	$P > F$	LSD $_{0.05}$	$P > F$	LSD $_{0.05}$	$P > F$	LSD $_{0.05}$
Treatment (T)	0.123	–	<0.001	4.1	0.124	–
Year (Y)	0.009	7.0	0.003	4.2	0.987	–
T × Y	0.595	–	<0.001	10.8	0.015	0.8

Values are means of two separate counts in 1999 and 2000 and of three separate counts in 1998.
[a] Plant counts for each replication were means of the untreated plot and four additional plots assigned to the post-emergence herbicide treatments not yet applied.

Table 4
Aboveground weed and pigeon pea dry matter at 111, 120, and 98 days after planting in 1998, 1999, and 2000, respectively

Treatment	Weeds (g m^{-2})				Pigeon pea (g m^{-2})			
	1998	1999	2000	Average	1998	1999	2000	Average
Hand-weeded	0.0	0.0	0.0	0.0	45	462	191	233
Untreated	185	656	267	369	8	189	27	75
Sulfentrazone + chlorimuron (1×)	90	648	678	472	17	206	257	160
Sulfentrazone + chlorimuron (2×)	0.2	331	328	220	23	415	225	221
Metribuzin (1×)	127	646	211	328	23	205	208	145
Metribuzin (2×)	16	674	410	367	37	251	187	158
Imazapic (1×)	0.1	184	0.0	61	33	452	236	240
Imazapic (2×)	0.1	28	14	14	50	481	238	256
Sethoxydim (1×)	125	707	224	352	12	197	54	88
Sethoxydim (2×)	111	680	283	358	7	177	43	76
Average	66	455	241		25	303	167	

Source of variation	Weeds ANOVA		Pigeon pea ANOVA	
	$P > F$	LSD $_{0.05}$	$P > F$	LSD $_{0.05}$
Treatment (T)	<0.001	20	<0.001	11
Year (Y)	<0.001	38	0.001	38
T × Y	<0.001	175	0.003	79

3 years, weed dry matter in imazapic treated plots was less than all of the other herbicide treatments, and at the higher application rate weed control was as effective as the hand-weeded treatment (Table 4). Weed density was greatest in 1999, followed by 2000 and then 1998, while the average dry matter per weed was nearly equal in 1998 (29 g plant^{-1}) and 1999 (32 g plant^{-1}) and substantially greater than that in 2000 (12 g plant^{-1}).

Averaged across years, pigeon pea dry matter in the imazapic and hand-weeded plots was greater than the other treatments. Untreated and the post-emergence sethoxydim treated plots had the least amount of pigeon pea dry matter (Table 4). The amount of weed dry matter of the sethoxydim treated plots was among the largest. Even though sulfentrazone + chlorimuron (1×) and the metribuzin (2×) pre-emergence herbicide treatments had weed dry matter values equal to or greater than the sethoxydim treatments, the pigeon pea dry matter was nearly two-fold greater for these pre-emergence treatments than those of the sethoxydim post-emergence treated plots (Table 4). Similar to the yearly ranking for weed dry matter, amounts of aboveground pigeon pea dry matter decreased in order of 1999 > 2000 > 1998, which corresponded to the more favorable warm-season temperature and rainfall patterns in 1999 and 2000 than 1998 (Fig. 1).

3.3. Wheat dry matter, grain yield, and N

Treatment × year effect was not significant ($P = 0.168$), and the main effect of year was not significant ($P = 0.565$) for total aboveground dry matter of mature winter wheat. Averaged across years, the dry matter from the hand-weeded treatment exceeded all but the 2× application rates of the pre-emergence sulfentrazone + chlorimuron and metribuzin treatments (Fig. 2). Wheat dry matter accumulation in plots treated with imazapic was less than all other treatments and, at most, only 32% of the dry matter of wheat grown on hand-weeded plots during the growth of the summer annual pigeon pea. Post-emergence sethoxydim treatments had wheat dry matter levels comparable to those of the metribuzin (1×) and the untreated plots (Fig. 2), all of which were only about 62% of the wheat dry matter from the hand-weeded treatment.

Treatment differences in wheat grain yield and above-ground N uptake (Fig. 3) followed a pattern similar to the total aboveground dry matter (Fig. 2). Grain yields among the hand-weeded and the pre-emergence herbicide treated plots were often greater than or equal to the other treatments made to the pigeon pea crop. Wheat grain yields from plots previously treated post-emergence with imazapic herbicide applied to pigeon pea were less than all other treatments and were only about 40% and 7% of the average grain yield

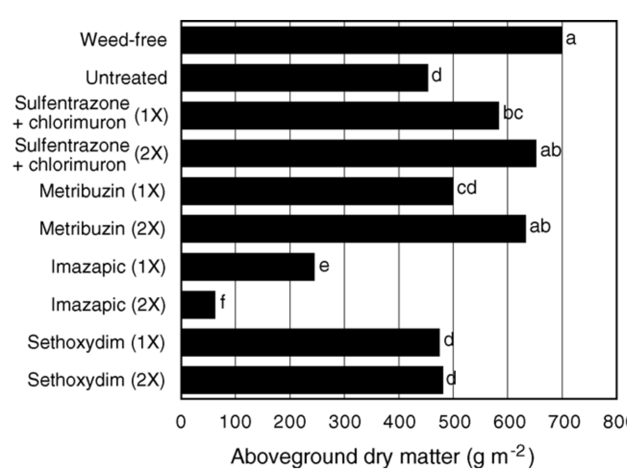

Fig. 2. Total aboveground dry matter of mature winter wheat planted in plots with different weed management controls applied to a summer crop of pigeon pea. Values are overall treatment means for the 1999–2000 and 2000–2001 winter wheat crop years. Bars with the same letter are not significantly different at the $P = 0.05$ level.

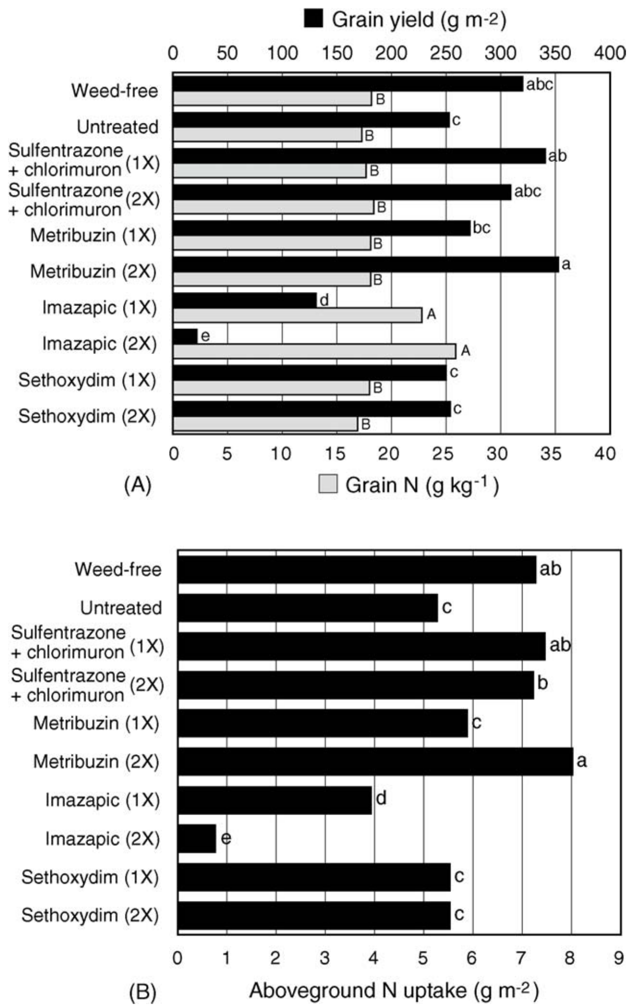

Fig. 3. Winter wheat grain yield and N (panel A) and total aboveground N uptake (panel B) of the 2000–2001 crop. Bars of each trait followed by the same letter are not significantly different at $P = 0.05$.

(331 g m^{-2}) of the highest yielding treatments (Fig. 3). Inversely matching the low yield of wheat grain in plots treated with imazapic was a grain N concentration ($\bar{x} = 24.4$ g kg^{-1}) that was significantly greater than all of the other treatments ($\bar{x} = 17.8$ g kg^{-1}). The aboveground N uptake of the wheat crop corresponded strongly ($r = 0.96$, $P < 0.001$) with the amount of aboveground dry matter (cf. Figs. 2 and 3).

4. Discussion

Neither early season nor late season stands of Georgia-2 pigeon pea averaged across the three growing seasons were affected adversely by the pre- and post-emergence herbicides, even when there was a two-fold increase in application rate according to product labeling appropriate for other legume crops (Tables 2 and 3). While the densities of pigeon pea were unaffected by herbicide treatment, visual symptoms of stunted growth were evident within 10 days after post-emergence application of imazapic, but this injury was markedly less than the chlorosis and stunting injuries to imazapic-treated cowpea (*Vigna unguiculata* (L.) Walp.) in an adjacent experiment (Bidlack, unpublished data). Although these symptoms disappeared, other pigeon pea cultivars and lines may not react as Georgia-2. Differential herbicide tolerance among soybean (*Glycine max* (L.) Merr.) cultivars is well documented. For example, tolerance to pre-emergence sulfentrazone + chlorimuron treatment (Swantek et al., 1998; Hulting et al., 2001) appears to be controlled by a tolerance dominate gene (Swantek et al., 1998). A wide range of tolerances to metribuzin also exists among soybean varieties (Wax et al., 1976; De Weese et al., 1989). The levels of herbicide injury to soybean are affected by cultural conditions and rates of application of pre-emergence metribuzin (Wax, 1977; Moomaw and Martin, 1978) and post-emergence imidazolinone herbicides (Mills and Witt, 1989; Newsom and Shaw, 1995; Young et al., 2003).

Compared to the hand-weeded treatment, survival of the slow growing pigeon pea seedlings in the untreated plots was not reduced by competition between weeds and pigeon pea plants for resources (Table 3). Even though survival of emerged pigeon peas was not adversely affected in the untreated plots, pigeon pea aboveground dry matter was significantly reduced (Table 4) as previously documented (e.g., Almodovar-Vega and Velez-Baez, 1980; Vaddi et al., 1999). The most abundant weeds were broadleaf (Tables 2 and 3); consequently, the post-emergence sethoxydim treatment, which controls annual and perennial grasses, had both abundant numbers and dry matter of broadleaf weeds that greatly reduced accumulation of pigeon pea dry matter to an amount similar to that of pigeon pea plants in untreated plots (Table 4). A yearly comparison of weed density and dry matter for the untreated plots reveals that the greatest amounts of weeds occurred following the fallow winter of 1999.

Averaged across years, the most effective weed control among the chemical treatments was achieved with post-emergence imazapic applications (Table 4). Coupled with this effective weed control were the best dry matter yields of pigeon pea, even though imazapic treatment caused temporary injury symptoms of chlorosis and stunting. In terms of weed control, both of the pre-emergence herbicides were effective in reducing the density of weeds, but those that escaped control grew large resulting in a total weed dry matter often similar to the untreated and sethoxydim grass herbicide treatments. Averaged across years there was a linear decrease ($\hat{y} = 249–0.331$ (weed dry matter); $R^2 = 0.65$, $P = 0.005$; derived from Table 4) in pigeon pea dry matter (g m^{-2}) as weed dry matter increased. Including weed density as a regressor along with weed dry matter improved the prediction of pigeon pea dry matter ($\hat{y} = 248 - 0.159$ (weed dry matter) $- 3.42$ (weed density); $R^2 = 0.96, P < 0.0001$). Among treatments with similar total weed dry matter, pigeon pea dry matter accumulation was more adversely affected when there were many weeds (untreated and sethoxydim plots) as opposed to the metribuzin treatments resulting in fewer large weeds (Tables 3 and 4).

Crop rotations with winter wheat have a recommended minimum interval of 4 months before planting after the use of sulfentrazone + chlorimuron, metribuzin, or imazapic on the previous crop. For the 1999–2000 wheat rotation, the interval between herbicide treatment and planting of wheat was 5 months for the pre-emergence applications of sulfentrazone + chlorimuron and metribuzin and 4 months for the post-emergence application of imazapic. However, the 2000–2001 wheat rotation was planted about 2.5 months after application of the pre-emergence herbicides and slightly less than 2 months after the imazapic application. Only imazapic applications to the preceding pigeon pea crop clearly had an adverse residual effect on aboveground dry matter productivity of the following wheat crop (Fig. 2). Wheat dry matter levels of all the other herbicide treatments were not significantly different from the untreated control and the hand-weeded treatments. For the 1999–2000 wheat crop, the detrimental effect of imazapic herbicide on wheat productivity occurred even though 4 months elapsed between herbicide application and planting of wheat. Compared to the hand-weeded control treatment, decreases in average wheat dry matter in plots previously treated with imazapic was rate dependent leading to a 65% reduction at 1×, which was further reduced at the 2× rate to only 91% of the wheat dry matter in the hand-weeded treatment. Other imidazolinones (imazaquin and imazethapyr) applied to soybean demonstrated no adverse effect to a following wheat crop (Johnson et al., 1995; Krausz et al., 1992). In our situation, the interval before wheat planting, particularly for the 2000–2001 wheat crop, and environmental conditions adversely affecting microbial activity (climate, and physical, chemical and biological soil properties) may have contributed to the persistence of imazapic as reported for the imidazolinone herbicides imazaquin and imazethapyr (Flint and Witt, 1997). Despite the adverse effects of imazapic in the pigeon pea–wheat rotation system, the release of winter wheat cultivars with a nontransgenic source of resistance to imidazolinone herbicides (Haley et al., 2003; Lazar et al., 2003) offers a management alternative to avoid potential negative residual effects of imazapic on wheat dry matter accumulation (Fig. 2), N uptake, and grain yield (Fig. 3).

The wide variation in abundance of weeds and pigeon pea dry matter between the untreated and hand cultivated hand-weeded treatment (Table 4) corresponded to significantly greater dry matter (Fig. 2) and total aboveground N uptake (Fig. 3B) of mature winter wheat that was grown on the preceding hand-weeded legume plots. For 1999 and 2000, the average final pigeon pea dry matter of the hand-weeded treatment was about 300% greater than that of the untreated plots, which had an average total dry matter (weeds + pigeon peas) of 570 g m^{-2} as compared to an average pigeon pea dry matter of 327 g m^{-2} for the hand-weeded treatment. Amounts of residual legume N (derived in part from N_2 fixation) should be greater for the hand-weeded treatment than the untreated plots, and the amount of soil residual mineral N available to the following wheat crop would be less in the preceding untreated plots that had greater total (weeds + pigeon peas) dry matter. Consequently, differences in wheat dry matter and N uptake between the untreated and hand-weeded treatments could be partly related to differences in residual N and would be consistent with similar positive responses of winter wheat to pigeon pea rotations grown in containers of soil (Rao et al., 2002b).

Except for sethoxydim, the other chemical treatments provided effective weed suppression (dry matter and/or number of weeds) allowing favorable pigeon pea dry matter accumulation. In Australia but not the U.S., metribuzin has been registered for use with pigeon pea. All of the herbicides we used carry grazing restrictions for annual legumes on their U.S. labels. These restrictions ranged from 40 days after application (soybean, metribuzin) to not graze or feed hay (soybean, sulfentrazone; peanut, imazapic). For producers wishing to use pigeon pea for hay or possibly as forage, these livestock use restrictions could prevent adoption, unless the U.S. labels are revised.

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References

Ali, M., 1991. Weed management in pigeonpea under rainfed conditions in India. Trop. Pest Manag. 37, 345–348.

Almodovar-Vega, L., Velez-Baez, A., 1980. Evaluation of metribuzin, prometryn, and chloamben for weed control in pigeon peas [*Cajanus cajan* (L.) Millsp.]. J. Agric Univ. P.R. 64, 29–32.

Brakke, M.P., Gardner, F.P., 1987. Juvenile growth in pigeonpea, soybean, and cowpea in relation to seed and seedling characteristics. Crop Sci. 27, 311–316.

Callaway, M.B., 1992. A compendium of crop and varietal tolerance to weeds. Am. J. Alt. Agric. 7, 169–180.

Dahiya, S.S., Chauhan, Y.S., Johnasen, C., Waldia, R.S., Sekhon, H.S., Nandal, J.K., 2002. Extra-short duration pigeonpea for diversifying wheat-based cropping systems in the sub-tropics. Exp. Agric. 38, 1–11.

De Weese, W.W., Wax, L.M., Carlson, W.C., Ciarletta, J.A., 1989. Response of soybean *Glycine max* cultivars to metribuzin in the field and greenhouse. Weed Tech. 3, 566–572.

Flint, J.L., Witt, W.W., 1997. Microbial degradation of imazaquin and imazethapyr. Weed Sci. 45, 586–591.

Haley, S.D., Lazar, M.D., Quick, J.S., Johnson, J.J., Peterson, G.L., Stromberger, J.A., Clayshulte, S.R., Clifford, B.L., Pester, T.A., Nissen, S.J., Westra, P.H., Peairs, F.B., Rudolph, J.B., 2003. Above winter wheat. Can. J. Plant Sci. 83, 107–108.

Hepperly, P.R., Rodríguez, R., 1986. Constraints to pigeon pea production under semi-arid conditions in Puerto Rico. J. Agric. Univ. P.R. 70, 25–35.

Hulting, A.G., Wax, L.M., Nelson, R.L., Simmons, F.W., 2001. Soybean (*Glycine max* (L.) Merr.) cultivar tolerance to sulfentrazone. Crop Prot. 20, 679–683.

Johnson, D.H., Talbert, R.E., Horton, D.R., 1995. Carryover potential of imazaquin to cotton, grain sorghum, wheat, rice, and corn. Weed Sci. 43, 454–460.

Krausz, R.F., Kapusta, A.G., Knake, E.L., 1992. Soybean *Glycine max* and rotationoal crop tolerance to cloimuron, clormazone, imazaquin, and imazethapyr. Weed Tech. 6, 77–80.

Laxman Singh, Chauhan, Y.S., Johansen, C. (Eds.), 1996. Prospects for growing extra-short-duration pigeonpeas in rotation with winter crops: Proceedings of the IARI/ICRISAT Workshop and Monitoring Tour, 16–18 October 1995, New Dehli, India. International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India.

Lazar, M.D., Haley, S.D., Quick, J.S., Johnson, J.J., Peterson, G.L., Stromberger, J.A., Clayshulte, S.R., Clifford, B.L., Pester, T.A., Nissen, S.J., Westra, P.H., Peairs, F.B., Rudolph, J.B., 2003. AP502 CL winter wheat. Can. J. Plant Sci. 83, 109–110.

Mills, J.A., Witt, W.W., 1989. Effect of tillage systems on the efficacy and phytotoxicity of imazaquin and imazethapyr in soybean *Glycine max*. Weed Sci. 37, 233–238.

Moomaw, R.S., Martin, A.R., 1978. Interaction of metribuzin and trifluralin with soil type on soybean *Glycine max* growth. Weed Sci. 26, 327–331.

Newsom, L.J., Shaw, D.R., 1995. Soybean (Glycine max) response to AC 263 222 and chlorimuron as influenced by soil moisture. Weed Tech. 9, 553–560.

Norman, M.J.T., Searle, P.G.E., Dankittipakul, N., Ingram, K.C., Baskoro, J.D., 1980. Evaluation of pigeon-pea *Cajanus cajan* as an autumn forage for coastal New-South-Wales Austrailia. Aust. J. Exp. Agric. Anim. Husb. 20, 55–62.

Pahwa, S.K., Prakash, J., Sharma, H.R., 1988. Effect of herbicides on the growth, nodulation, and symbotic nitrogen fixation in pigeon pea *Cajanus cajan* L. Millsp. Crop Res. Hisar. 1, 131–140.

Phillips, W.A., Rao, S.C., 2001. Digestibility and nitrogen balance of diets containing cottonseed meal, alfalfa, or pigeon pea as the protein source. [Online] [6 p.] Available at http://www.cipav.org.co/lrrd/lrrd13/6/phil136.htm (verified 10 May 2005). Livest. Res. Rural Dev. 13 (6) (0121-3784).

Rao, S.C., Coleman, S.W., Mayeux, H.S., 2002a. Forage production and nutritive value of selected pigeonpea lines in the southern Great Plains. Crop Sci. 42, 1259–1263.

Rao, S.C., MacKown, C.T., Bidlack, J.E., 2002b. Biomass and nitrogen traits of summer pigeon peas and winter wheat grown for three rotations in containers. Commun. Soil Sci. Plant Anal. 33, 897–912.

Rao, S.C., Phillips, W.A., Mayeux, H.S., Phatak, S.C., 2003. Potential grain and forage production of early maturing pigeonpea in the southern Great Plains. Crop Sci. 43, 2212–2217.

SAS Institute, 2002. JMP Statistics and Graphics Guide. Version 5.0. SAS Inst., Cary, NC.

Semidey, N., Almodovar, L., 1987. Oxyfluorfen: a candidate herbicide for weed control in pigeon peas. J. Agric. Univ. P. R. 71, 277–285.

Shetty, S.V.R., 1981. Some aspects of weed management in pigeonpeas. In: ICRISAT Proceedings of the International Workshop on Pigeonpeas, vol. 1, 15–19 December 1980, Patancheru, A.P., India, pp. 137–148.

Singh, S.P., 1996. Prospects for varietal improvement in extra-short-duration pigeonpeas. In: Laxman Singh, et al. (ed.) Prospects for Growing Extra-short-duration Pigeonpeas in Rotation with Winter Crops: Proceedings of the IARI/ICRISAT Workshop and Monitoring tour, 16–18 October 1995, New Delhi, India. International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India, pp. 86–95.

Swantek, J.M., Sneller, C.H., Oliver, L.R., 1998. Evaluation of soybean injury from sulfentrazone and inheritance of tolerance. Weed Sci. 46, 271–277.

Vaddi, M.H., Pujari, B.T., Desai, B.K., 1999. Studies on weed management practices in pigeonpea (*Cajanus cajan* (L.) Millsp.). World Weeds 6, 161–166.

Wax, L.M., 1977. Incorporation depth and rainfall on weed control in soybeans with metribuzin. Agron. J. 69, 107–110.

Wax, L.M., Stoller, E.W., Bernard, R.L., 1976. Differential response of soybean cultivars to metribuzin. Agron. J. 68, 484–486.

Young, B.G., Young, J.M., Matthews, J.L., Owen, M.D.K., Zelaya, I.A., Hartzler, R.G., Wax, L.M., Rorem, K.W., Bollero, G.A., 2003. Soybean development and yield as affected by three postemergence herbicides. Agron. J. 95, 1152–1156.